Using Interferometry
to Achieve Micro-Arcsecond Astrometry
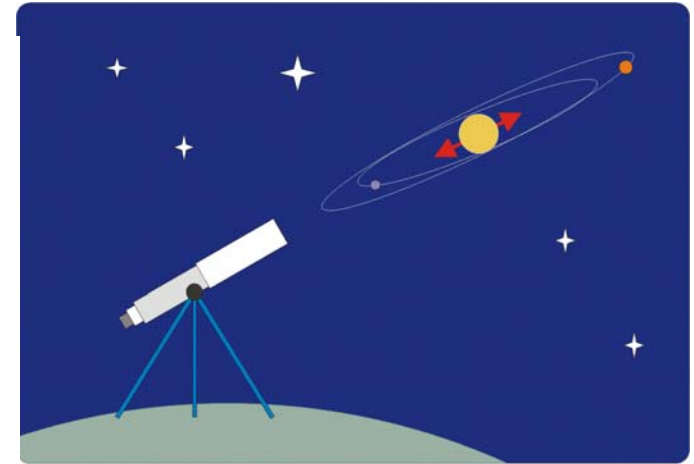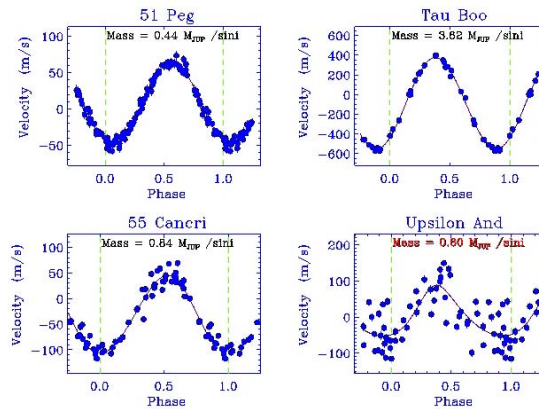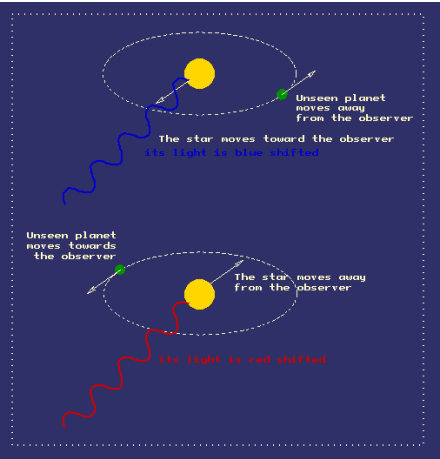
Bijan Nemati

Exoplanet Science and Technology Fair, JPL

22 February 2008

NORTHROP GRUMMAN
Space Technology

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Method 1: Measure the star's motion back and forth towards us ("Radial velocity") – Lower limits down to ~ 20 M_{Earth}
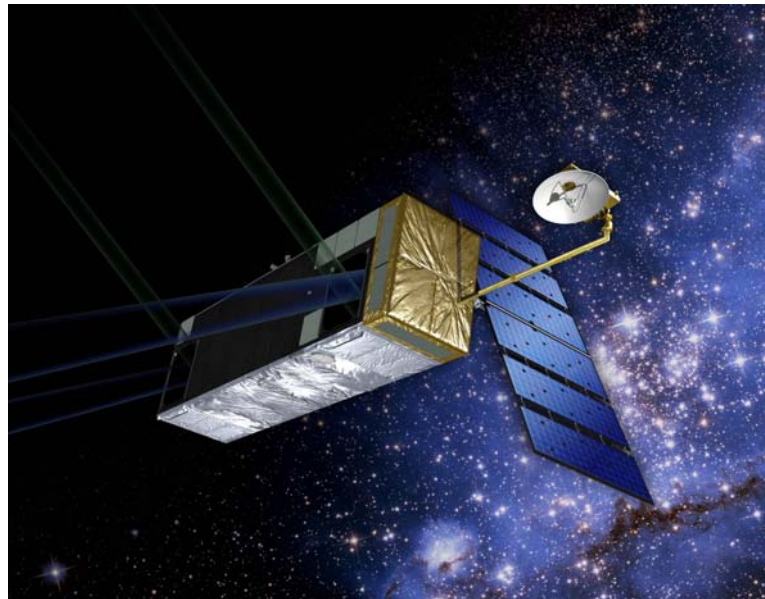

Method 2: Measure wobble of the star relative to the background ("Astrometry") – can do down to ~ 1 M_{Earth}

wobble due to earth is at the < μas level!
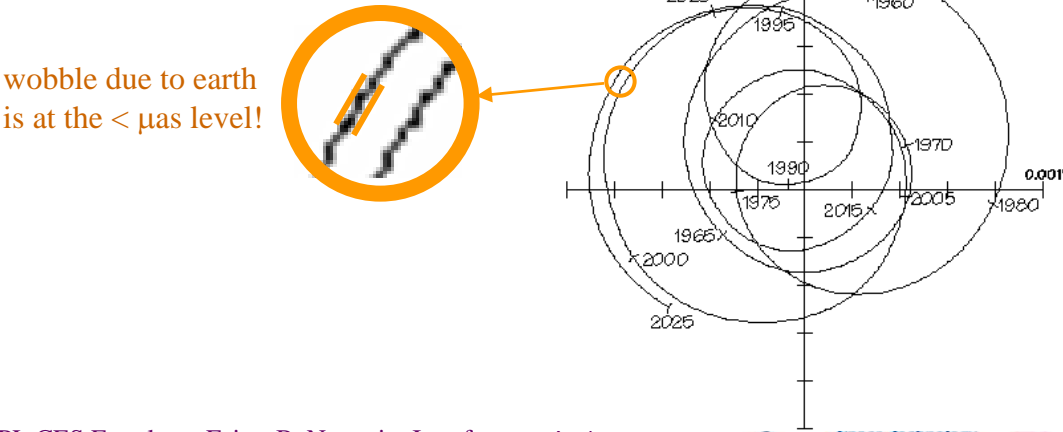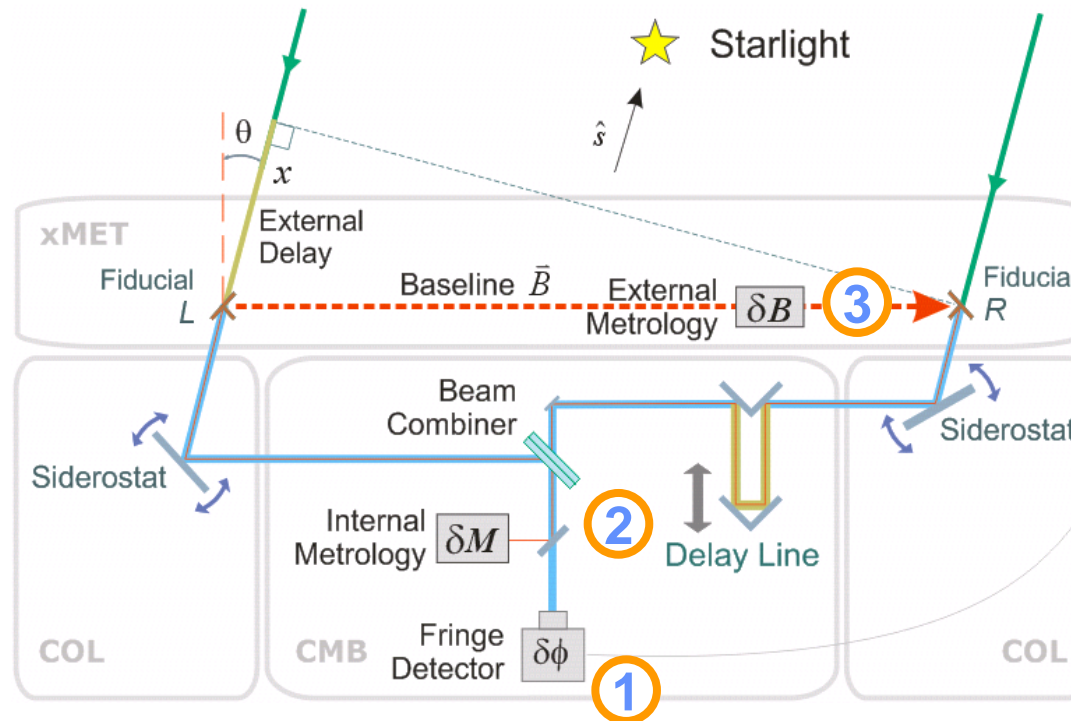
- A 9m baseline interferometer with 30 cm apertures is equivalent to a 3 m telescope for astrometry
- In the special case of nearby exoplanet searches, an interferometer has a greater advantage.
  - The 9m baseline interferometer with 2 deg FOR is like a 30 m telescope with a 12 arcmin FOV.
- Beyond Photometry
  - Adequate sampling of the telescope PSF for the purposes of uas astrometry requires giant focal planes – on the order of 1 Gpix (and mosaic focal planes may not do)
  - Systematic errors in CCD centroiding for a focal plane that is critically sampled is probably limitted to $(1/2000)(\lambda/D)$ A few tens of uas may be the limit for a 1-2 m telescope, goes linearly with diameter
  - The equivalent error for an interferometer is the measuring of the white light delay. Here a precision of $(1/60,000)*\lambda/D$ has been demonstrated in the laboratory.

National Aeronautics and Space Administration
Jet Propulsion Laboratory
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① Fringe Detector – Total starlight pathlength difference

② Internal Metrology – Internal starlight pathlength difference

③ External Metrology – Baseline vector

$$T_L - T_R = (E_L + I_L) - (E_R + I_R)$$
$$\delta T = \delta E + \delta I$$
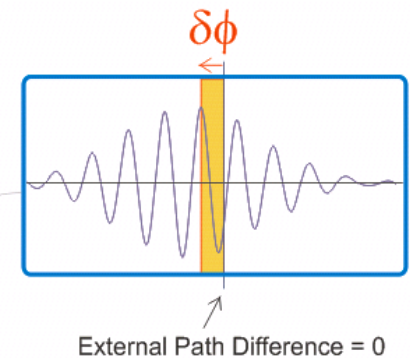$$\delta E = \vec{b} \cdot \hat{s}$$
$$= b \cos \alpha$$
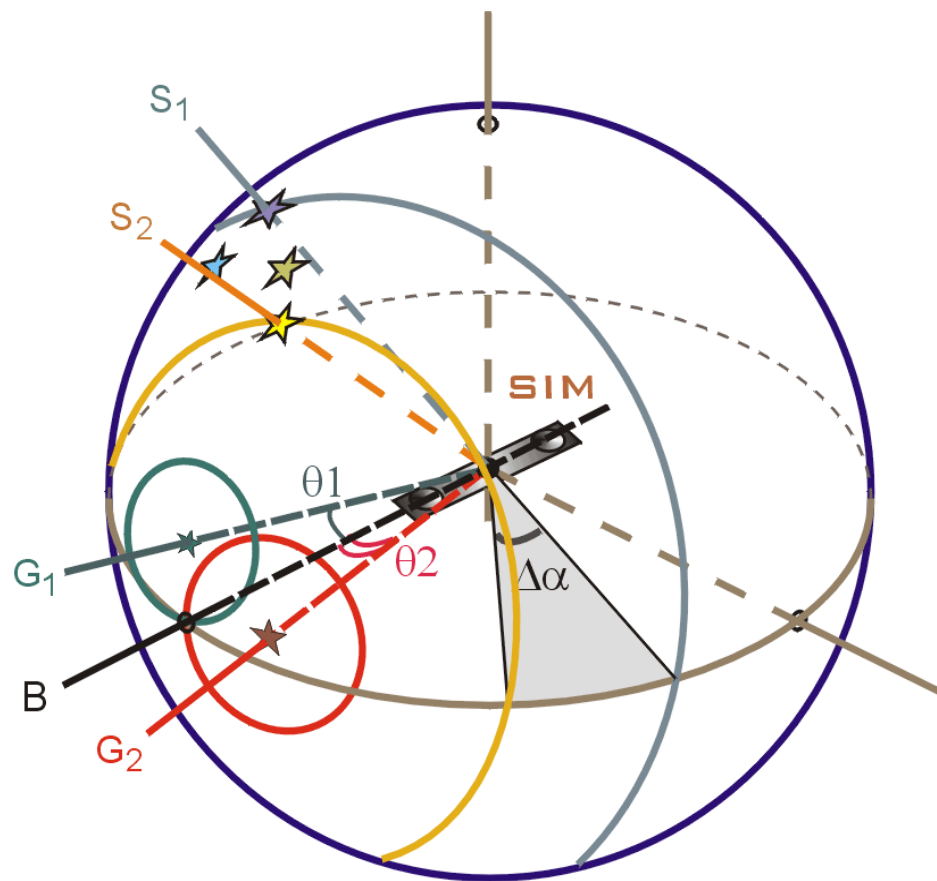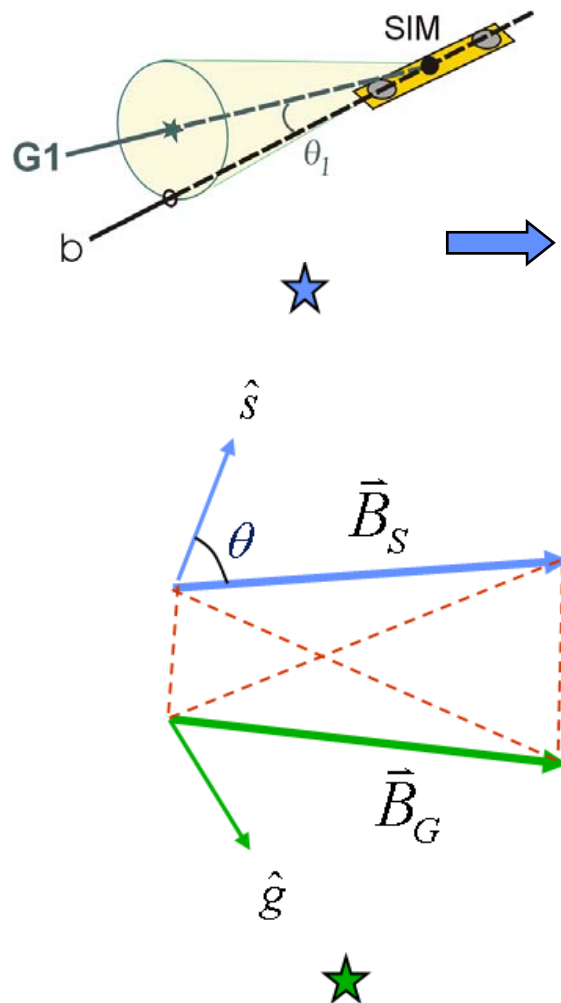$$\delta I = \delta M + C$$
$$x \equiv \delta \phi - \delta M$$
$$x = \delta T - (\delta I - C) = \delta E + C$$
$$= \vec{b} \cdot \hat{s} + C$$

Science and Guide Interferometers

National Aeronautics and
Space Administration
Jet Propulsion Laboratory
California Institute of Technology

- To detect stellar wobble due to an Earth mass planet from 10 pc away, requires ~ 1 uas precision per 'visit'

- This corresponds to ~ 44 pm in delay error (total).

$$44\,pm \quad 1\mu as \quad 9m$$

- The main obstacles to getting down to this level are:

  1. Noise
     - Atomic & Structural Vibrations
       - Light beams average over large number of atoms on the optics surfaces
       - Vibrations along light paths are actively controlled to a few nanometers
     - Electronic Noise
       - Temporal averaging, low-noise electronic design

  2. Thermal Drifts
     - Affect Structure, Optics, Electronics
       - Narrow-angle: Chop between target and reference
       - Wide-angle: Use Grid observations to remove linear temporal drift each hour

  3. Systematic Errors
     - Field Dependent Biases: **Astrometric Grid** is used to solve for biases
     - Other Systematics: Calibration, Engineering design

SIM PlanetQuest

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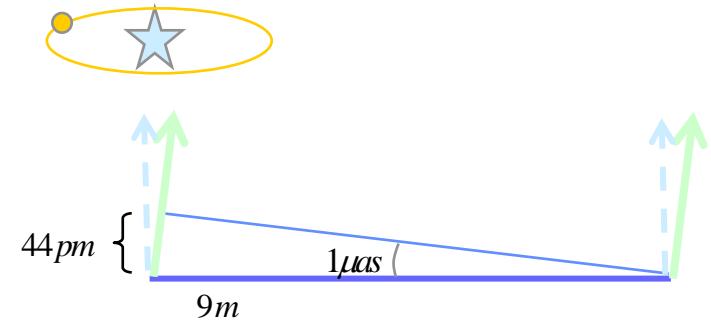
Picometer Metrology Truss Testbed (Kite)

- A real example of how this works is shown below in data from SIM's external Metrology Testbed (Kite)
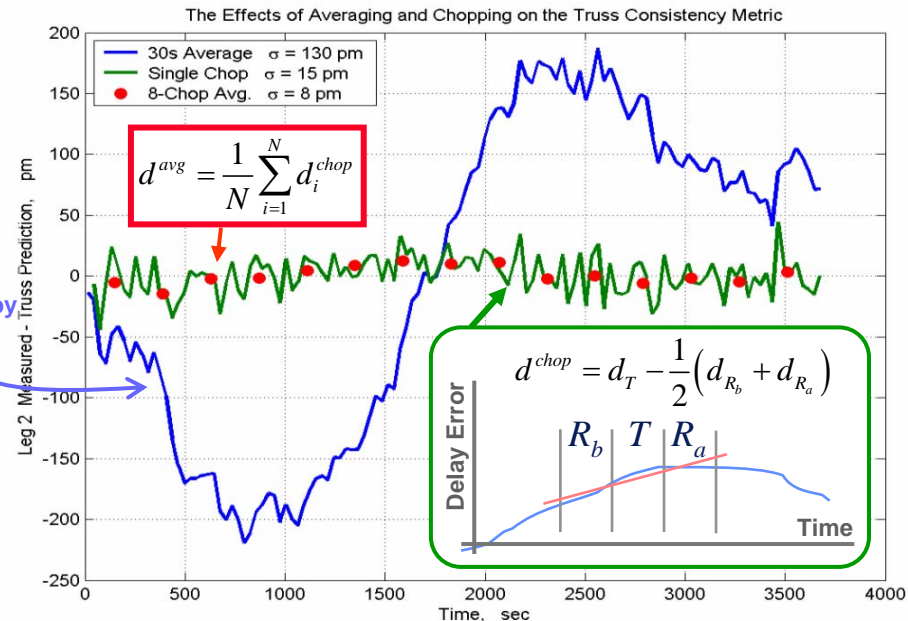
  - The raw gauge output shows noise at the ~30 nm level

  - The Narrow-Angle metric, however, is only a few picometers

Kite Quasi-static Run (Dec. 2, '03) - Sample Rate = 100 Hz

The Error Metric: $\Delta = L_2^{measured} - L_2^{Estimated}$

average down & blow-up by ~ 2000X

The Effects of Averaging and Chopping on the Truss Consistency Metric

30s Average σ = 130 pm
Single Chop σ = 15 pm
8-Chop Avg. σ = 8 pm

$$d^{avg} = \frac{1}{N}\sum_{i=1}^{N} d_i^{chop}$$

$$d^{chop} = d_T - \frac{1}{2}\left(d_{R_b} + d_{R_a}\right)$$

$R_b \mid T \mid R_a$
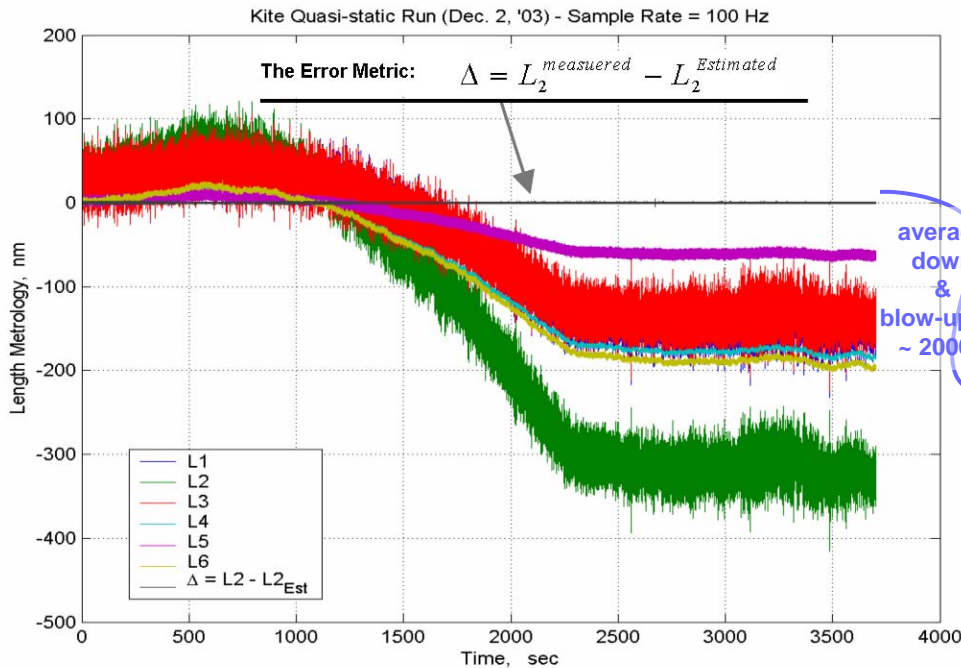
- Create a single interferometer with a SIM-like field of regard
- Create an equally good inverse interferometer to act as a pseudo star
- Demonstrate that the white light delay and the internal delay can be measured with accuracy at the picometer level

MAM Testbed Narrow Angle Runs   (Sep. 2-8, '03)
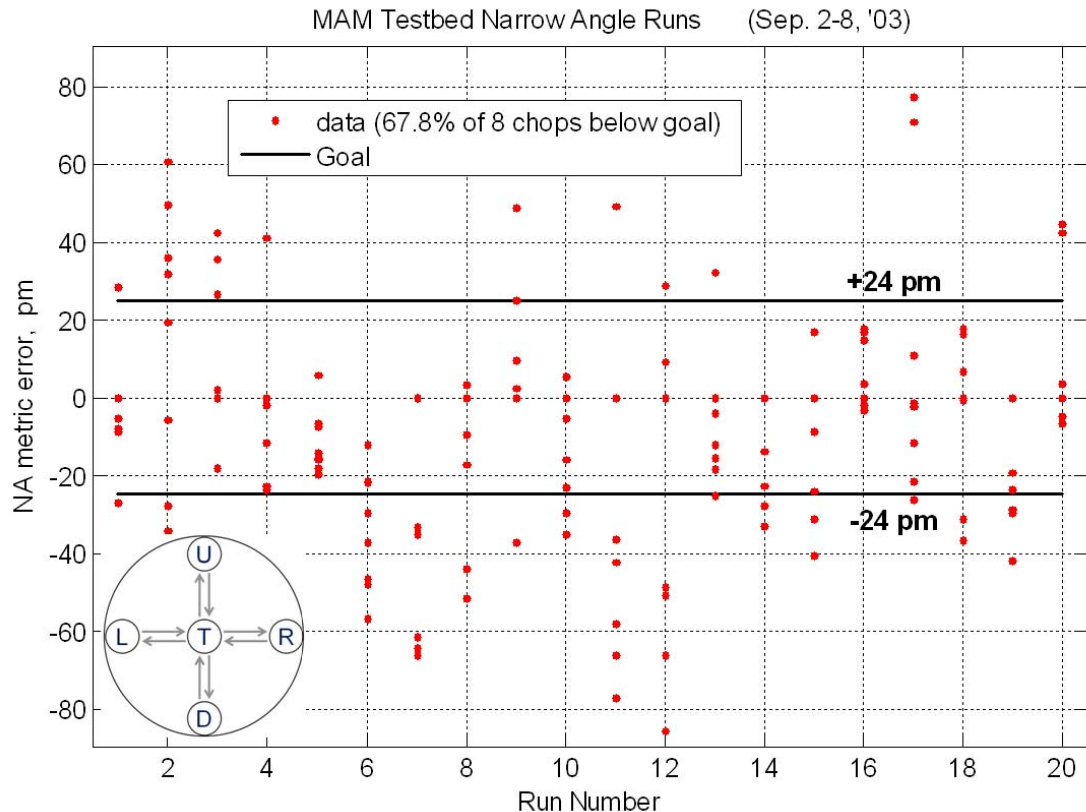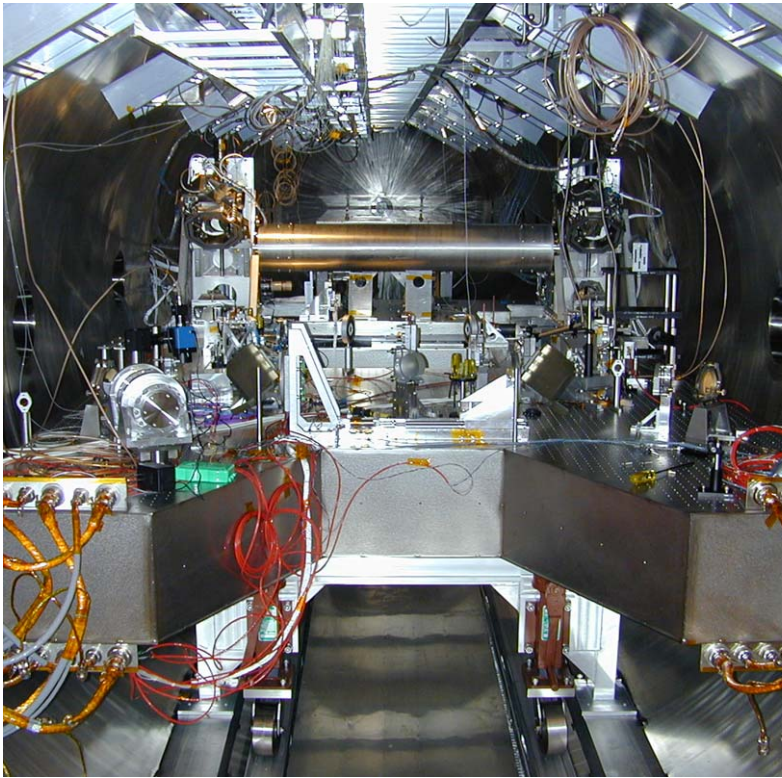
Expectations for SIM Performance

- For planet finding, the SIM narrow-angle chop breaks down most errors into effectively random errors
- Instrumental errors in the SIM testbed (chopped) does integrate down as sqrt(T)
  - At least down to 1~2 picometer after 10^5 sec

The effect of averaging NA chops on MAM random errors (Feb. 10-16, '06 quasistatic)
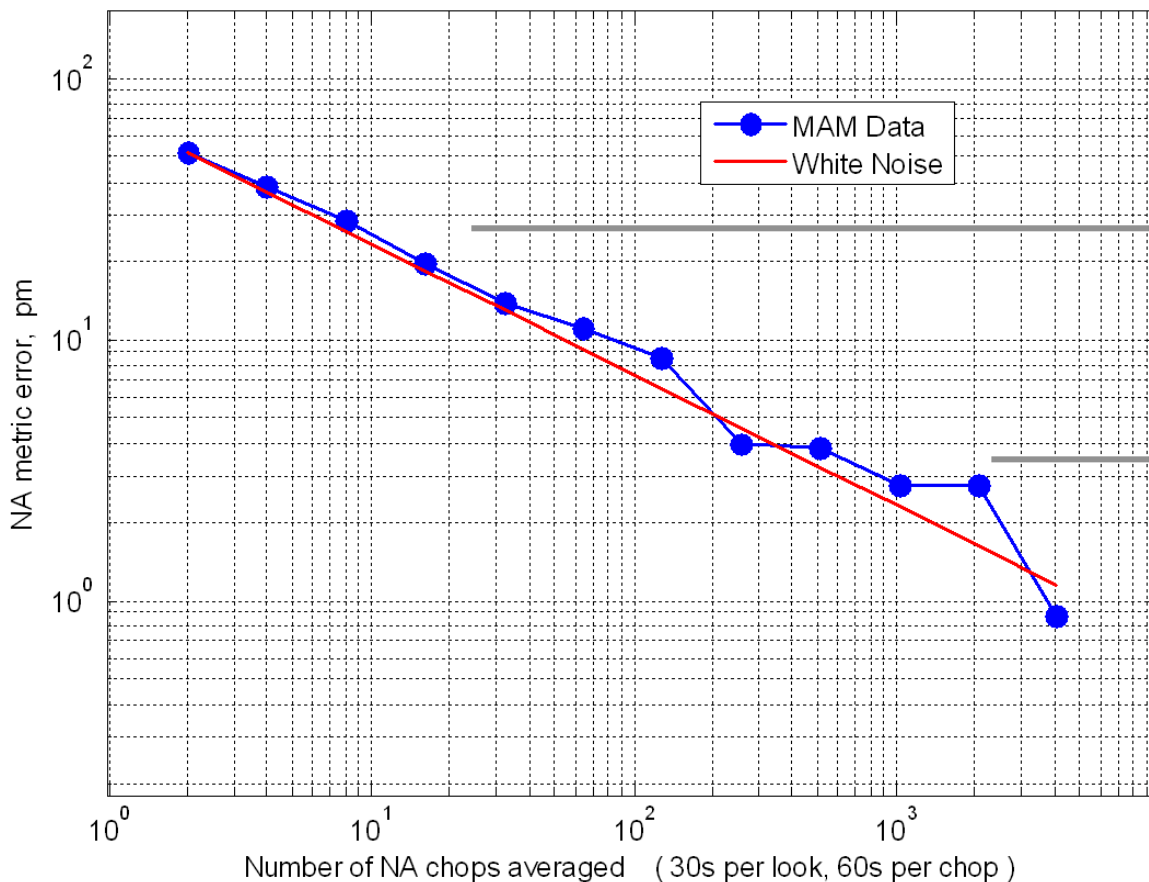
Terrestrial Planet search
Single epoch precision 1μas

Terrestrial Planet search
5yr mission precision 0.14μas

Systematic error floor
< 100 femto-arcsec

Backup

Exoplanet Science & Techology Fair

Friday, February 22, 2008   Von Karman   Agenda 4 -DRAFT

Start	Duration	Topic	Presenter
8:30 AM	0:30	Coffee, Pastries, & Poster Viewing	
9:00 AM	0:10	Welcome and Introductions	Langer, Werner, Traub, Unwin
9:10 AM	0:40	*Keynote talk:* Exoplanets as Individual Worlds	Laughlin, Greg
9:50 AM	0:08	The Palomar Testbed Interferometer: Status & Development	Akeson, Rachel
9:58 AM	0:08	Angular Diameters of Exoplanet Host Stars	von Braun, Kaspar
10:06 AM	0:08	The NASA Star & Exoplanet Database (NStED)	Kane, Stephen
10:14 AM	0:08	Outer Solar System Chronology from Satellite Geophysics	Johnson, Torrence
10:22 AM	0:08	Exoplanet Detection with the Electric Field Conjugation Algorithm	Give'on, Amir
10:30 AM	0:08	Kepler Mission	Gautier, Nick
10:38 AM	0:35	Coffee Break & Poster Viewing	
11:13 AM	0:08	SIM & SIM Life Architecture Trades & Performance	Goullioud, Renaud
11:21 AM	0:08	Achieving MicroArcsecond Astrometry with SIM	Nemati, Bijan
11:29 AM	0:08	Multiple Planets with SIM	Pan, Xiaopei
11:37 AM	0:08	Detection of Earth in the Presence of Sunspot Noise	Catanzarite, Joseph
11:45 AM	0:08	Detecting Giant Plants Around M, L, T Dwarfs in the Infrared	Pravdo, Steven
11:53 AM	0:08	The Emma X-Array Architecture for TPF-I/Darwin	Lay, Oliver
12:01 PM	0:08	TPF-I Technology Plans & Status	Lawson, Peter
12:09 PM	0:08	Talk	Serabyn, Eugene
12:17 PM	0:08	Exoplanets in the APD Investment Strategy	Werner, Michael
12:25 PM	0:35	Invited lunch talk: Planning for Exoplanet Missions	Elachi, Charles
1:00 PM	0:35	Lunch Break & Poster Viewing	
1:35 PM	0:08	Coronagraph Design Options for Exoplanet Finding & Characterization	Levine, Marie
1:43 PM	0:08	Terrestrial Planet Finder Coronagraph Performance Model	Shaklan, Stuart
1:51 PM	0:08	Lab Demos of Coronagraphic Imaging: The High Contrast Imaging Testbed	Trauger, John
1:59 PM	0:08	The Lighter Side of TPF: Scientific Gains of Different Architectures	Hunyadi, Sarah
2:07 PM	0:08	Phase Mask Coronagraphy: Scientific Results & Perspectives	Mawet, Dimitri
2:15 PM	0:08	Design & Fabrication of TPF Coronagraph Testbed Masks	Bala
2:23 PM	0:08	Talk	Gunson, Michael
2:31 PM	0:08	Keck Interferometer	Colavita, Mark
2:39 PM	0:08	Stratospheric Seeing & Contrast Limits for a Balloon-borne Coronagraph	Chen, Pin
2:47 PM	0:08	Orbit Options for Finding Exoplanets	Lo, Martin
2:55 PM	0:35	Coffee Break & Poster Viewing	
3:30 PM	0:08	*Invited talk:* TBD	McCleese, Dan
3:38 PM	0:08	Searching for Terrestrial Planets Around Low Mass Stars	Tanner, Angelle
3:46 PM	0:08	The Peculiar Periodic YSO WL 4	Plavchan, Peter
3:54 PM	0:08	Extrasolar Kuiper Belts Imaged with the Spitzer Space Telescope	Stapelfeldt, Karl
4:02 PM	0:08	HST Imaging of Debris Disks	Krist, John
4:10 PM	0:08	Protostellar Disks & the Earliest Phases of Planet Formation	Yorke, Harold
4:18 PM	0:08	Probing Interstellar Dust with Space-Based Coronagraphs	Turner, Neal
4:26 PM	0:08	Detecting Molecules in Exoplanet Atmospheres with Spitzer & Hubble	Swain, Mark
4:34 PM	0:08	The Fiber Nuller: Detection of Faint Companions Close to Bright Stars	Hanot, Charles
4:42 PM	0:08	A Dilute Aperture Visible Nulling Coronagraph Instrument (DAVINCI)	Shao, Michael
4:50 PM	0:08	Planet Forming Discs Around Dying Stars?	Deroo, Pieter
4:58 PM	0:40	Poster Viewing	
5:38 PM	0:00	STEPS: JPL's Astrometric Exoplanet Survey (Poster only)	Shaklan, Stuart
		Adjourn	

Long Integrations, instrumental errors

- Instrumental errors in the SIM testbed (chopped) does integrate down as sqrt(T)
  - At least down to 1~2 picometer after 10^5 sec

allan deviation of 30/30 sec chop pairs 40 hrs
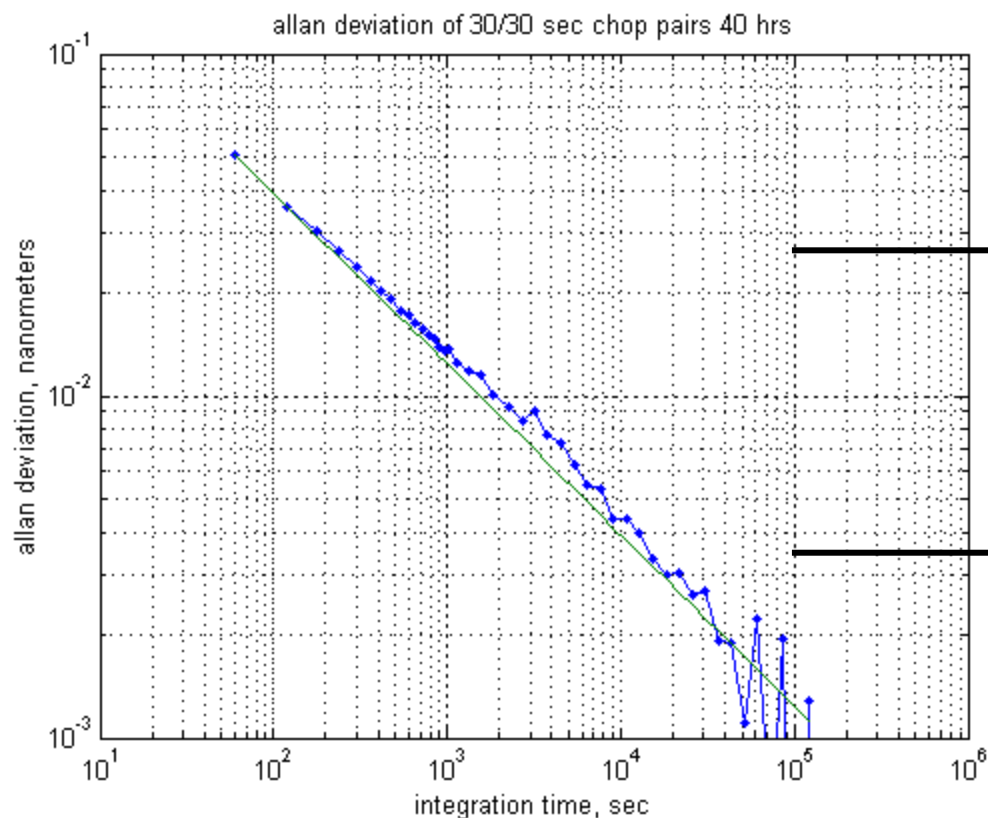
Terrestrial Planet search
Single epoch precision 1µas

Terrestrial Planet search
5yr mission precision 0.14µas

Systematic error floor
< 100 femtoarcsec

MAM testbed March 2006